1 Introduction

Every vehicle needs a transmission!

1.1 Preface

All vehicles, aircraft and watercraft included, require transmissions in order to convert torque and engine speed. Transmissions are distinguished in accordance with their function and purpose – e.g. selector gearboxes, steering boxes and power take-offs. This book deals exclusively with transmissions for road vehicles as well as for vehicles designed for both on-road and off-road use (Figure 1.1).

Figure 1.2 provides an overview of common transmission designs and their systematic classification. Further details can be found in Chapter 6 "Vehicle Transmission Systems". Dual clutch transmissions are assigned to automatic transmissions with various gear ratios due to their similarity with respect to control and functionality.

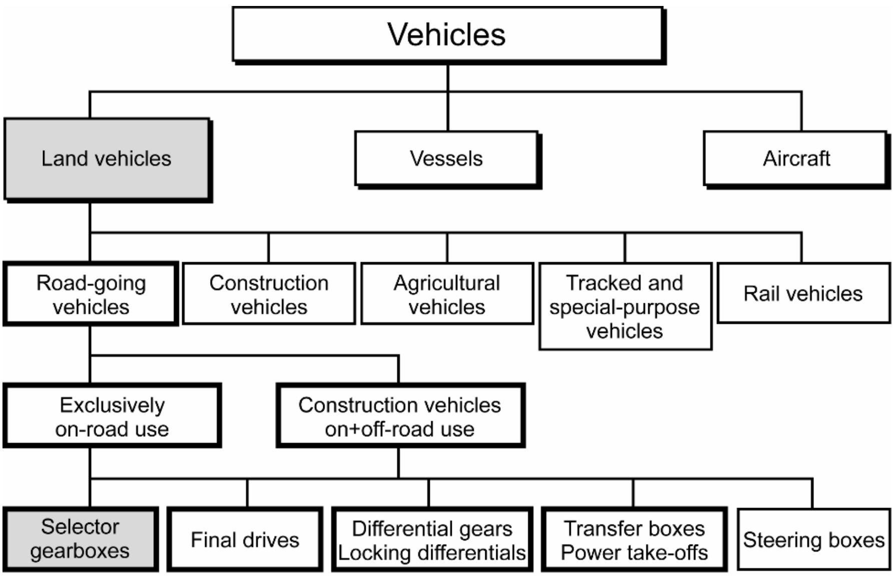

Fig. 1.1. Definition of the term "automotive transmission" as this book uses it

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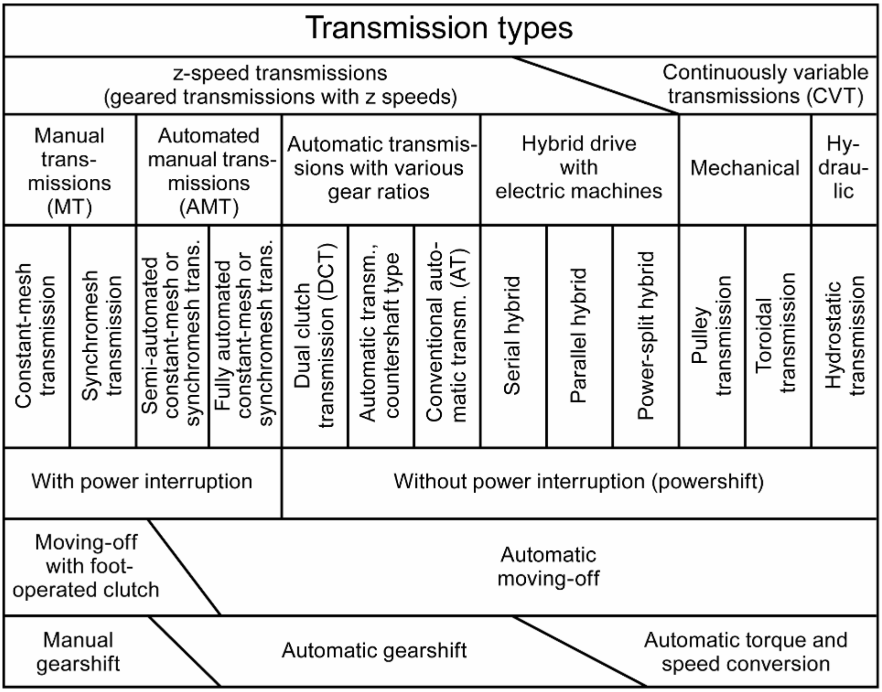


Fig. 1.2. Systematic classification of automotive transmission types

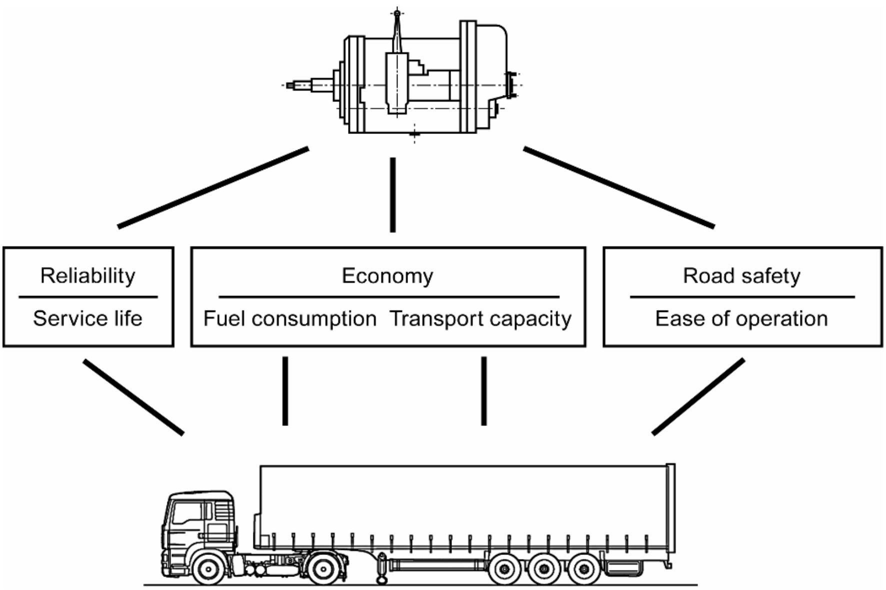


Fig. 1.3. The effect of the transmission on basic attributes of a vehicle

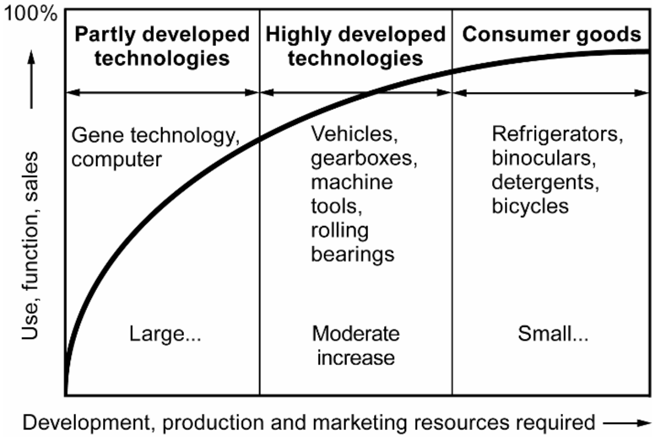
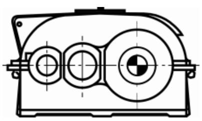
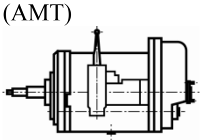
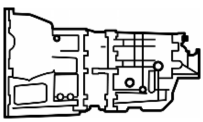


Fig. 1.4. Achievable increase in the practical value of a product by additional development effort

The task of a transmission is to convert the traction available from the drive unit, satisfying requirements placed on it by the vehicle, the road, the driver and the environment. Technical and economical competitiveness are essential here. In addition to the driving and transport performance of passenger and commercial vehicles, transmissions are of central importance with respect to reliability, fuel consumption, ease of operation and road safety (Figure 1.3).

Table 1.1. Comparison between industrial and automotive transmissions

Transmission	Number of speeds (forward)	Ratio 1st gear/overall gear ratio	Power (kW)	Input torque (Nm)	Mass (kg)	Specific power (kW/kg)
Industrial 	1	12.5 –	330	2100	680	0.48 100%
Commercial vehicle (AMT) 	16	14.1 17.0	397	2600	266	1.49 300%
Passenger car (MT) 	6	4.2 5.1	294	500	46	6.39 1300%

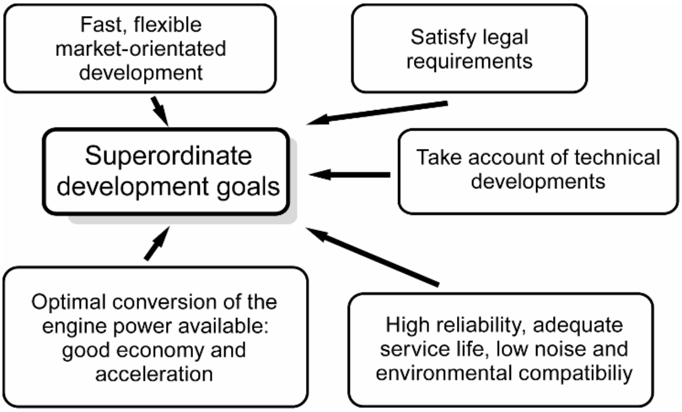


Fig. 1.5. Superordinate development goals for vehicle transmissions

Automotive transmissions are mass-produced products of a high technical and technological order. They are classified as highly developed technologies (Figure 1.4). What is remarkable is the specific power P_{spec} in kW/kg of commercial vehicle transmissions, which is more than three times more than that of industrial transmissions (Table 1.1), despite the fact that automotive transmissions have more speeds. On the other hand, industrial transmissions have to be designed for a longer service life.

Basic innovations in the field of automotive transmissions are no longer to be expected. Instead, we are witnessing a process of gradual evolution. This process is characterized by system thinking focused on the factors Environment ⇔ Traffic ⇔ Vehicle ⇔ Engine/Transmission and by the use of electronics for operational, control and monitoring processes. The superordinate design objectives for automotive transmissions resulting from these tendencies are shown in Figure 1.5.

Vehicle transmission development must be fast and market-oriented. Customers' preferences, especially in the case of commercial vehicles, must be accommodated flexibly. Legal conditions, kW/t-regulation or emission policies for example, must be met. Furthermore, emotional aspects like driving pleasure must also be taken into consideration.

The main goal when designing an automotive transmission is an optimal conversion of the traction available from the engine into the traction force of the vehicle over a wide range of road speeds. This must be done such that there is a favorable compromise between the number of speeds, the climbing and acceleration performance and fuel consumption. Further technical and technological developments should obviously be considered – reliability and service life as well. It is also essential to have regard for environmental and social considerations.

The design of vehicle transmissions should always stay within the planning horizon for new vehicles (Figure 1.6). During the developmental phase of a vehicle, a corresponding transmission must also be created or further developed. To this end, new manufacturing technologies for mass production must also be prepared and introduced.

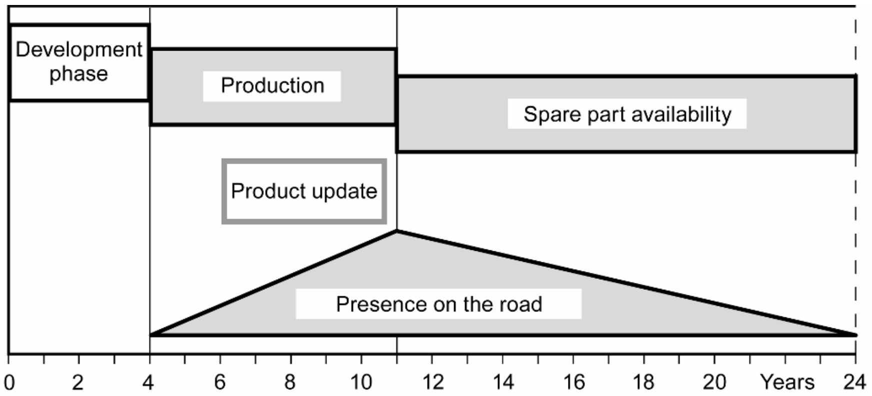


Fig. 1.6. Time dimensions and planning horizons in the automotive industry, from [1.1]

After the end of the production phase, it should be guaranteed that spare parts are available. For this purpose, the life cycles of additional components, including semiconductor components, have to be taken into consideration.

This book seeks to present the automotive transmission development process as a whole (Figure 1.7). It should show ways of thinking that go beyond mere component design. Regardless of which product is at hand, it is always necessary to assess the total system in which that product will later be employed. Such a system overview is indispensable and will be presented in Chapter 2.

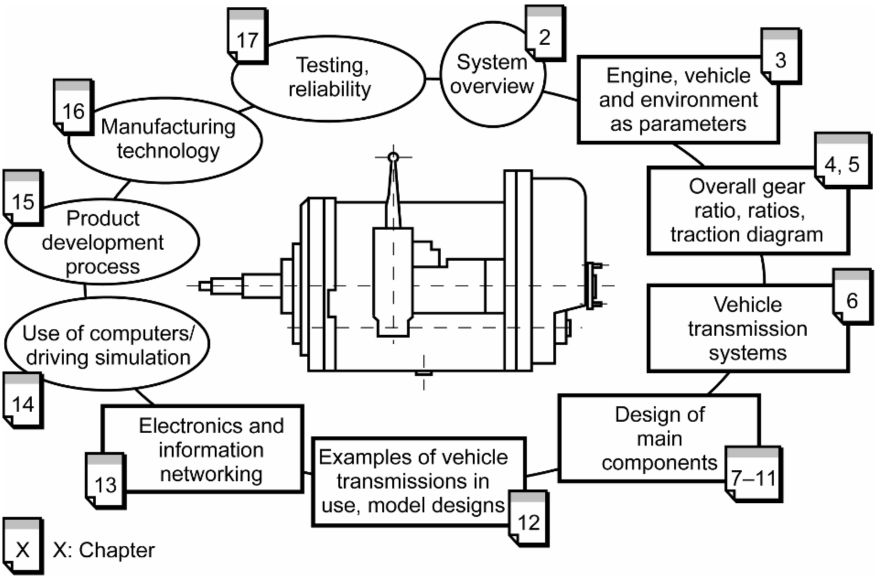


Fig. 1.7. The tasks involved in developing automotive transmissions, overview of chapters

Automotive transmissions are decisively influenced by the vehicle, the engine and the road profile. Without basic knowledge of these factors, meaningful developments are impossible.

Chapter 3 shows the interaction between power required and power available. The first development task focused directly on vehicle transmission is then selecting the range of ratios to be covered, the "overall gear ratio". In conjunction with selecting the number of speeds z, the gear ratio of the individual speeds, the resultant gear steps and the gear ratio of the final drive, the interaction of the vehicle and its transmission system can be evaluated and defined. Observing the road profile, it must be decided whether the vehicle is being sufficiently accelerated and whether the required climbing power and the specified maximum speed v_{max} are reached. We can then establish at the same time whether the transmission unit also permits economical driving – driving with low amounts of fuel consumption in particular. This is dealt with extensively in Chapters 4 and 5.

Creative design, which is indispensable, is complemented by systematic design. Here, a functional analysis is carried out during the conceptual phase. Solutions for individual functions must be found, evaluated and joined together to make an overall solution, i.e. the transmission design. Chapter 6 provides the information regarding the vehicle transmission systems necessary for this.

Following this in Chapters 7 to 11 are the layout and design of the most important components of a transmission: gearwheels, shafts, bearings, synchronizers, clutches, parking locks, pumps as well as hydrodynamic clutches and converters. A treatment of all the details involved in highly developed computation and simulation methods would go beyond the scope of this book. We have instead confined ourselves to the basics of calculation methodology and operations.

In Chapter 12, the structure of various transmission designs and important detailed solutions are explained with the help of a plentiful amount of design examples. Electronic transmission controls built with microprocessors have been the standard in automatic transmissions since 1982. They are among the most complex electronic components in the vehicle and are undergoing a very dynamic development with respect to both hardware and software. Chapter 13 explores this topic and deals with their integration and interconnection with other control devices in the vehicle.

Tools and parameters for the development of automotive transmissions are handled in the latter part of the book. Chapter 14 is dedicated to calculation and simulation tools. In Chapter 15, we take a look at the product development process. Manufacturing technology has a large influence on transmission design, competitiveness and quality. Chapter 16 provides insight into the broad and innovative field of machining, assembly and final inspection.

Quality is a decisive competitive factor. The final customers are interested above all in the reliability and service life of the overall system. Methods for planning and guaranteeing quality as well as corresponding testing programs and test stations are described in Chapter 17.

Of particular concern in this book is to show the reader different approaches and to supply data as amply as possible regarding practical development work on automotive transmissions. As Dudeck put it, "The task of engineering science is,

among other things, to refine complicated models to the point of simplicity”. This book strives towards that aim.

1.2 History of Automotive Transmissions

Knowledge of the past and of the state of the Earth adorns and nourishes the human spirit /Leonardo da Vinci/

Learn from the past for the future! Development engineers and designers should have a grasp of the historical development of their products. Then they can estimate what progress is still possible and what technological potential the current product development has already realized. Such knowledge compliments that of systematic design (see Chapter 15).

1.2.1 Basic Innovations

Basic innovations are discoveries, inventions and new developments, without which products of today could not have been developed. They lead in turn to further discoveries, inventions, new developments and designs that culminate inevitably in new products (Figure 1.8).

In the course of such developments, certain phenomena should be explained and researched in order to guarantee that the product will function reliably.

Table 1.2. Examples of fundamental innovations in automotives and automotive transmissions

4000 BC	Mesopotamian vase with a picture of a cart	**1829**	*Stephenson* Rail vehicle, steam locomotive
2500 BC	Wheels made of two semicircular wooden discs, presumably with leather tyres	**1877**	*Otto* Patent for four-stroke gas engine with compression
2000–1000 BC	Spur gears with pin wheel gear as drive element for water scoops (Sakie, Figure 1.10), worm gears for cotton gins	**1885**	*Benz* Three-wheeler with internal combustion engine
500 BC	Greek scholars discover the principles of mechanics	**1897**	*Bosch* Magneto-electric ignition
200 BC	Lever, crank, roller, wheel, hoist, worm gear and gearwheel are in use	**1905**	*Föttinger* Hydrodynamic torque converter
1754	*Euler’s* law of gears for gearwheels, involute toothing	**1907**	*Ford* Mass production of model T; the passenger car becomes a mass-produced item
1769	*Watt* Patent for steam engine	**1923**	*Bosch* Injection pump
1784	*Watt* Gearbox with constant-mesh engagement	**1925**	*Rieseler* Automatic passenger car transmission with torque converter and planetary gear set

Table 1.2 is an attempt to retrace the seminal innovations in mechanical engineering that have led to the motor vehicle and thus to automotive engineering.

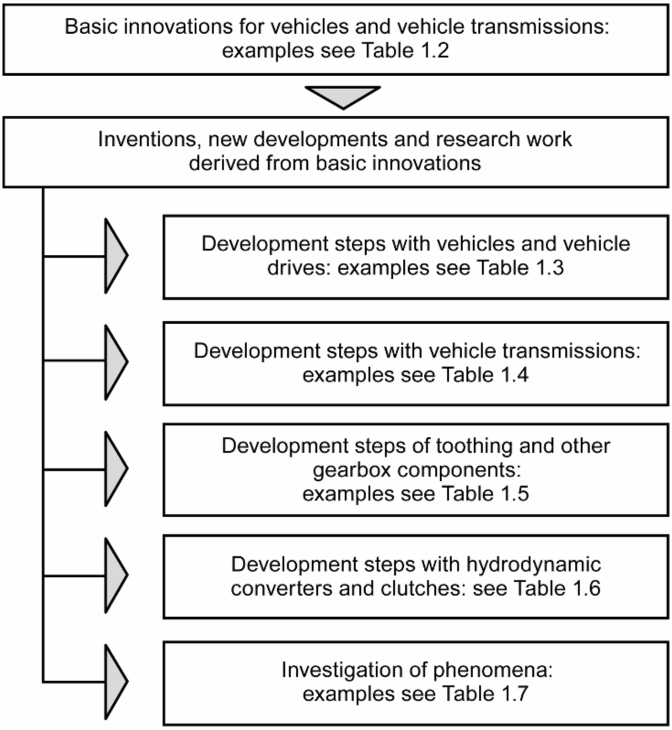


Fig. 1.8. Product developments are built upon basic innovations

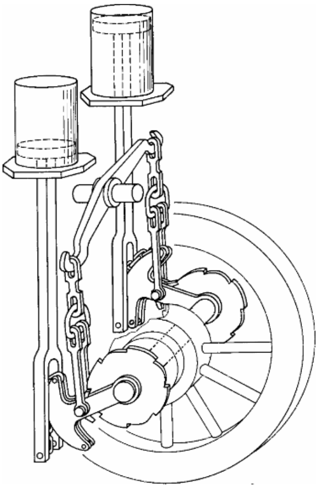


Fig. 1.9. Conversion of reciprocal movement into rotary movement. Twin-cylinder power unit with opposed pistons in the steam passenger car designed by Cugnot (1725 to 1804)

1.2.2 Development of Vehicles and Drive Units

The idea of equipping an engine with a gear unit in order to adjust speed and torque to the power output required is 100 years older than our present-day automobile with its official birth date of 1886. In the early days of the engine, the problem was how to convert the reciprocating motion of the piston into rotary movement. One possible solution is shown in Figure 1.9. The historical development of the transmission is thus closely tied to that of all engines (see Table 1.3).

Table 1.3. A chronology of important developments in vehicles and drive units

5000–500 BC	First technical inventions known: wheel, cart, gearwheel
1500	*Dürer* Sketch of a self-propelled vehicle
1690	*Papin* designs an atmospheric steam engine with cylinder and pistons
1769	*Cugnot* Steam vehicle with rectifier transmission
1784	*Watt* Double-acting steam engine with rotary movement and flywheel
1800	*Trevithick* Patent for high-pressure steam engine
1801	*Trevithick* Use of steam vehicle to carry passengers
1801	*Artamonow* Metal bicycle with pedal cranks
1814	*Stephenson* First steam locomotive
1817	*Drais* Steerable road wheel
1832	*Pixii* Rotating alternating current generator
1845	*Thompson* Invention of the pneumatic tyre
1862	*Lenoir* Double-acting gas piston engine
1866	*Siemens* Discovery of the dynamo-electric principle and design of an operational dynamo
1877	*Otto* Patent for four-stroke gas engine with compression
1884	*Parsons* Patent for steam turbine
1885	*Benz* Three-wheeler with combustion engine
1885	*Daimler* Motorcycle
1886	*Daimler/Maybach* Four-wheel motor car
1888	*Dunlop* Pneumatic rubber tyre
1889	*Maybach-Daimler* Steel wheeled passenger car with open 2-speed transmission
1897	*Bosch* Controlled electric magneto ignition
1897	*Diesel* Diesel engine; heavy fuel engine with compression ignition
1903	*Wright brothers* Powered flight
1907	*Ford* Introduction of mass production line
1926	*Gregoire* Constant-velocity joint. The Tracta joint opens the door to mass-produced front-wheel drive
1934	*Porsche* Project draft of the Volkswagen
1935	*Opel* designs the first frameless body for mass production vehicles
1959	Presentation of the BMC Mini, which will be the archetype for compact cars
1970	*Thyssen Henschel* Transrapid maglev monorail
1979	*Mercedes and BMW* Introduction of electronic engine control units and digital ABS
1980	*France* TGV high-speed trains
1989	*Audi* Introduction of direct injection and exhaust driven turbochargers for passenger car diesel engines
1992	After the Japanese vehicle manufacturers the European ones are introducing multi-valve engines in series production
1997	Common-rail injection in passenger car diesel engines

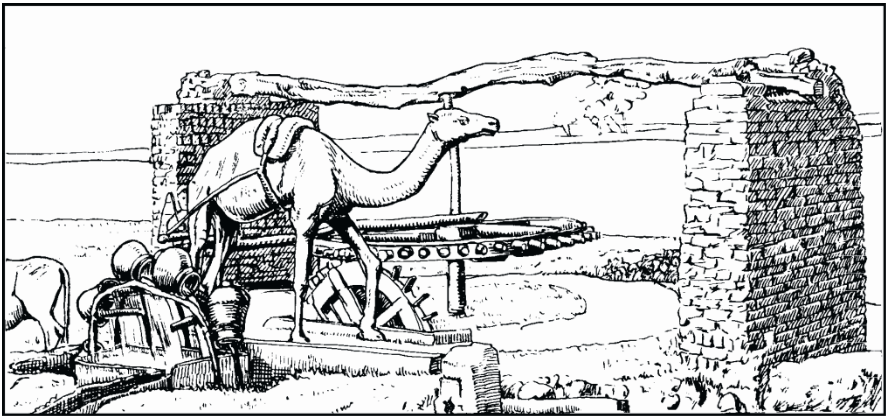


Fig. 1.10. An early transmission system! Egyptian water wheel (Sakia) in Luxor, approximately 2000 to 1000 BC

1.2.3 Stages in the Development of Automotive Transmissions

Gears were doubtlessly used over 1000 years ago for enhancing human and animal labour. Similarly to bullock gear systems, still used for water supply in Egypt today, the two mating parts interlock by means of wooden pins or teeth (Figure 1.10).

The first drawings of gear systems date from the Middle Ages. Motor power was lacking and thus muscle power had to be used in its place. Human "machines" had to do the heavy work in the process. The first "vehicle transmissions" originated. In an etching by Albrecht Dürer from about 1500, the limited human power stroke is converted into propulsive force by means of a thrust crank, an angular gear and a spur gear stage.

Table 1.4 provides examples for important stages in the development of automotive transmissions. Note that all essential elements and design principles for transmissions had already been developed by 1925. Since then, further progress has pursued the goals of increasing service life and performance, reducing weight and noise reduction and optimising operability. There are four basic lines of development (Figure 1.11, see also Figure 1.2):

- mechanical z-speed transmissions (including automated ones),
- automatic transmissions with various gear ratios,
- continuously variable mechanical or hydrostatic transmissions and
- hybrid drives.

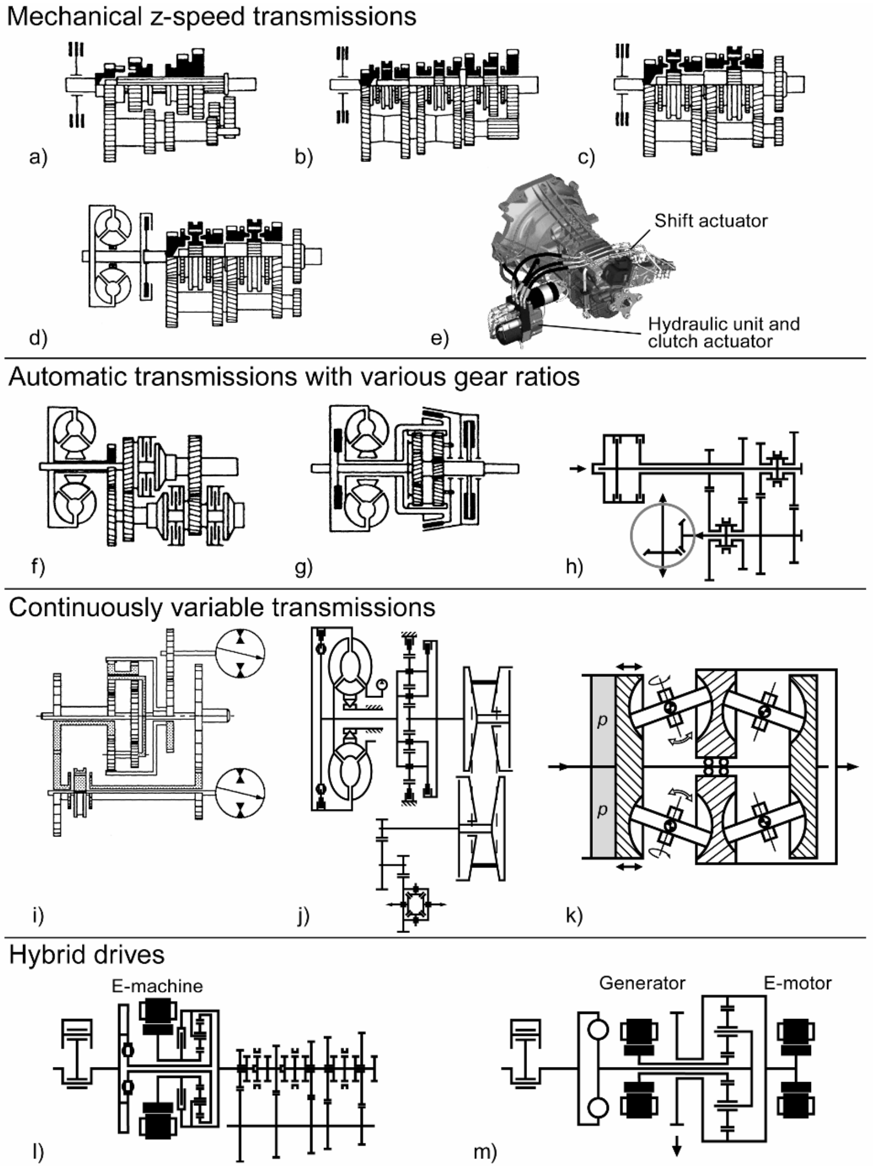


Fig. 1.11. Development sequence of passenger and commercial vehicle transmissions. *a* Transmission with sliding gear engagement; *b* transmission with constant-mesh engagement; *c* synchromesh transmission; *d* torque converter clutch transmission; *e* "Add-On"-automated manual gearbox; *f* countershaft-type automatic transmission; *g* conventional automatic transmission; *h* dual clutch transmission; *i* hydrostatic continuously variable transmission with power-split; *j* mechanical continuously variable transmission with taper discs; *k* friction gear, toroidal; *l* 1-E machine hybrid with z-speed transmission; *m* 2-E machine hybrid with summarising gear (power-split)

Table 1.4. Examples of important stages in the development of vehicle transmission

1784	*Watt* stipulates that steam engines require additional ratios for road-going vehicles	**1900**	*Lang* 3-speed geared transmission with constant-mesh wheels and draw key shifting
	Watt patents variable-speed gearbox with dog clutch engagement and constant mesh of gearwheels (Figure 1.12)	**1900**	*Diamant Speed Gear Company* Helical gear transmission
1821	*Griffith* 2-speed transmission with sliding gears (Figure 1.12)	**1905**	*Pittler* Hydraulic drive system with hydro pump and hydro motor
1827	*Pecqueur* First differential in a road-going vehicle (Figure 1.12)	**1906**	*Renault* Pneumatic transmission with piston compressor and piston engine
1834	*Bodmer* Planetary transmission with stallable ring gear body using brake belt	**1906**	*Didier* Two-stage planetary gear transmission with shifting using brake band and clutch of the planetary gear via friction plate face clutch
1849	*Napier/Anderson* 2-speed belt transmission (Figure 1.12)	**1907**	*Renault* Hydrostatic transmission with axial piston pump and axial piston motor
1879	*Selden* Patent enclosed sliding gear transmission with reverse gear and clutch (Figure 1.12)	**1907**	*Ford* Mass production of the model T with 2-speed planetary gear
1885	*Marcus* Cone clutch for motor vehicles	**1915**	*ZF Soden transmission* 4-speed all constant-mesh transmission with constant-mesh gearwheels with preselector shifting and with synchronizing aids
1886	*Benz* Belt-driven bevel gear differential (Figure 1.12)	**1925**	*ZF* Commercial vehicle standard gearbox with spur toothed sliding gears
1889	*Maybach-Daimler* 4-speed transmission with sliding gears (Figure 1.13)	**1925**	*Rieseler* Automatic passenger car transmission with torque converter and planetary gear set
1890	*Peugeot* Complete powertrain with sliding gear drive (Figure 1.13)	**1926**	*Cotal* 3-speed planetary gear with automatic shifting via three electromagnetic clutches
1899	*Buchet* Continuously variable belt transmission with axially adjustable taper discs	**1928**	Development of the Trilok converter – a precondition for modern hydromechanical “conventional” automatic transmissions
1899	*Krauser/Schmidt* Continuously variable friction gear with taper discs	**1928**	*Maybach* Overdrive auxiliary gearbox for reducing engine speed; shifting by means of override face dogs, and ground helical-cut gearwheels to reduce noise
1899	*Darracq - Léon - Bollée* 5-stage variable-speed belt “transmission gearbox”	**1929**	*ZF Aphon transmission* Helical-cut 4-speed transmission with multi-plate synchronizers
1899	*Oliverson - Killingsbeck* Continuously variable belt transmission with axially adjustable taper discs		
1900	*Reeves-Pulley* Continuously variable V-belt transmission with thrust links and axially adjustable taper discs		
1900	*Léo* 3-speed transmission with face dog clutch engagement, integral differential and chain drive reverse gear		

Table 1.4. *(continued)*

1931	*DKW F1* with driven front wheels. Transverse-mounted 2-cylinder 2-stroke engine
1932	*Wilson transmission* Multi-stage planetary coupled gear with identical ring gears that are alternately fixed against the housing by means of brake belts
1934	*ZF All-synchromesh gearbox* 4-speed gearbox, helical cut, all speeds synchronized
1939	*General Motors Hydra-Matic transmission* First mass-produced conventional automatic transmission: 13 million produced; hydrodynamic clutch, 4-speed planetary transmission
1939	*ZF* 4-speed transmission, helical cut, prototypes with electro-magnetic multi-plate clutches
1940	*Franke* Patent on dual clutch transmissions
1948	*General Motors* Dynaflow-transmission with polyphase converter and 2-speed Ravigneaux planetary gear set
1950	*ZF* AK6-55 6-speed commercial vehicle transmission, all speeds with dog clutch engagement
1950	*Packard* Ultramatic transmission. Conventional automatic transmission with torque converter lock-up clutch, 2-stage 2-phase converter and 2-speed planetary gear
1950	*Van Doorne "Variomatic"* Mass production of continuously variable V-belt transmission with axially adjustable taper discs (diameter adjustment)
1952	*Borg-Warner "Warner-Gear"-transmission* Conventional automatic transmission with Trilok converter and 3-speed planetary gear set
1953	*Borgward* Automatic transmission with converter and 3-speed spur gear drive with electrohydraulic shifting
1953	*ZF* Hydromedia transmission for buses; 3-speed transmission with converter and hydraulically activated multi-plate clutches
1957	*ZF* S 6-55, 6-speed commercial vehicle transmission, first fully synchronized commercial vehicle transmission
1958	*Smith* Magnetic-particle dual clutch with rear-mounted 3-speed spur gear transmission and electrically activated dog clutches
1961	*Daimler Benz* 4-speed automatic transmission, of 2-range design with hydrodynamic clutch
1962	*Eaton* 9-speed commercial vehicle transmission with power-split to two countershafts for a shorter overall design length
1965	*ZF* 3 HP 12, 3-speed-automatic transmission for passenger cars: converter without lock-up clutch, 3-stage planetary gear set and hydraulic actuation
1967	*VW* Semi-automatic transmission with torque converter clutch and rear-mounted 3-speed geared transmission
1970	*ZF* 5K/S 110 GP, 9-speed commercial vehicle transmission (1+4x2) with dog clutches or synchronized and rear-mounted range-change unit in planetary design
1970	Various companies develop a torque converter clutch transmission for commercial vehicles with a torque converter lockup clutch and secondary 6–8 speed transmission
1971	*Sundstrand "Responder"* Mass produced hydrostatic commercial vehicle gearbox with power-split through planetary gear set
1972	*Turner* Commercial vehicle transmission with output constant gear and synchromesh on the countershaft to increase service life

Table 1.4. *(continued)*

1975	*Van Doorne* Continuously variable passenger car transmission with steel thrust link chain and axially adjustable taper discs
1978	5-speed passenger car gearboxes with increased overall gear ratio to reduce fuel consumption
1979	*ZF Ecosplit* 16-speed commercial vehicle transmission with integrated front-mounted splitter unit and rear-mounted range-change unit
1980	Trilok converter with lock-up clutch in automatic passenger car transmissions
1983	*Eaton/Fuller TwinSplitter* 12-speed commercial vehicle transmission with 4-speed main gearbox and two rear-mounted splitter units
1985	*Porsche* Re-discovery of the dual clutch principle as an automatic transmission for passenger cars
1987	*ZF* Semi-automation for commercial vehicle transmissions, AVS automatic preselection gear-shifting
1989	*Porsche* Automatic transmission with finger-tip control and adaptive shifting strategies
1990	Mass production of conventional automatic transmissions with torque converter, lock-up clutch, five speeds and electrohydraulic shift
1991	Renewed interest in alternative powertrain concepts: electrical and hybrid drives
1996	*Fendt Vario* Hydrostatic continuously variable power-split transmission with two driving ranges for tractors
1998	*Getrag* Automated 6-speed transmission in multi-range design for Smart compact cars
1998	*ZF AS-Tronic* Fully automated commercial vehicle transmission with 12 or 16 speeds in 2-countershaft design
1999	*Audi Multitronic* Mass production of continuously variable transmissions. Tensional link chain and wet master clutch
1999	*VW* 6-speed manual transmission for front-wheel drive with transverse engine
2000	*Toyota* Mass production of hybrid drives with the Prius 1
2001	*ZF* 6-speed automatic transmission for standard drive
2002	*Aisin* 6-speed automatic passenger car transmission for front-wheel drive with transverse engine
2003	*VW* Dual clutch transmission with 6 speeds for front-wheel drive with transverse engine
2003	*Mercedes-Benz* 7-speed automatic transmission for standard drive
2005	*Getrag* 7-speed automated manual transmission for BMW M5
2006	*Aisin* 8-speed automatic passenger car transmission for standard drive
2008	*VW* Dual clutch transmission with dry clutch and 7 speeds
2009	*ZF* 8HP, 8-speed automatic passenger car transmission for standard drive with optimised efficiency

The invention of the steam engine soon brought forth the desire to adjust the available power to the intended use. The first steam-powered vehicles were driven by ratchet gears (Figure 1.9). Climbing gradients required higher ratios than driving on an even surface. In 1784, James Watt patented the constant-mesh gear with constantly meshing gearwheels still common today (Figure 1.12). Variable-speed transmission was born.

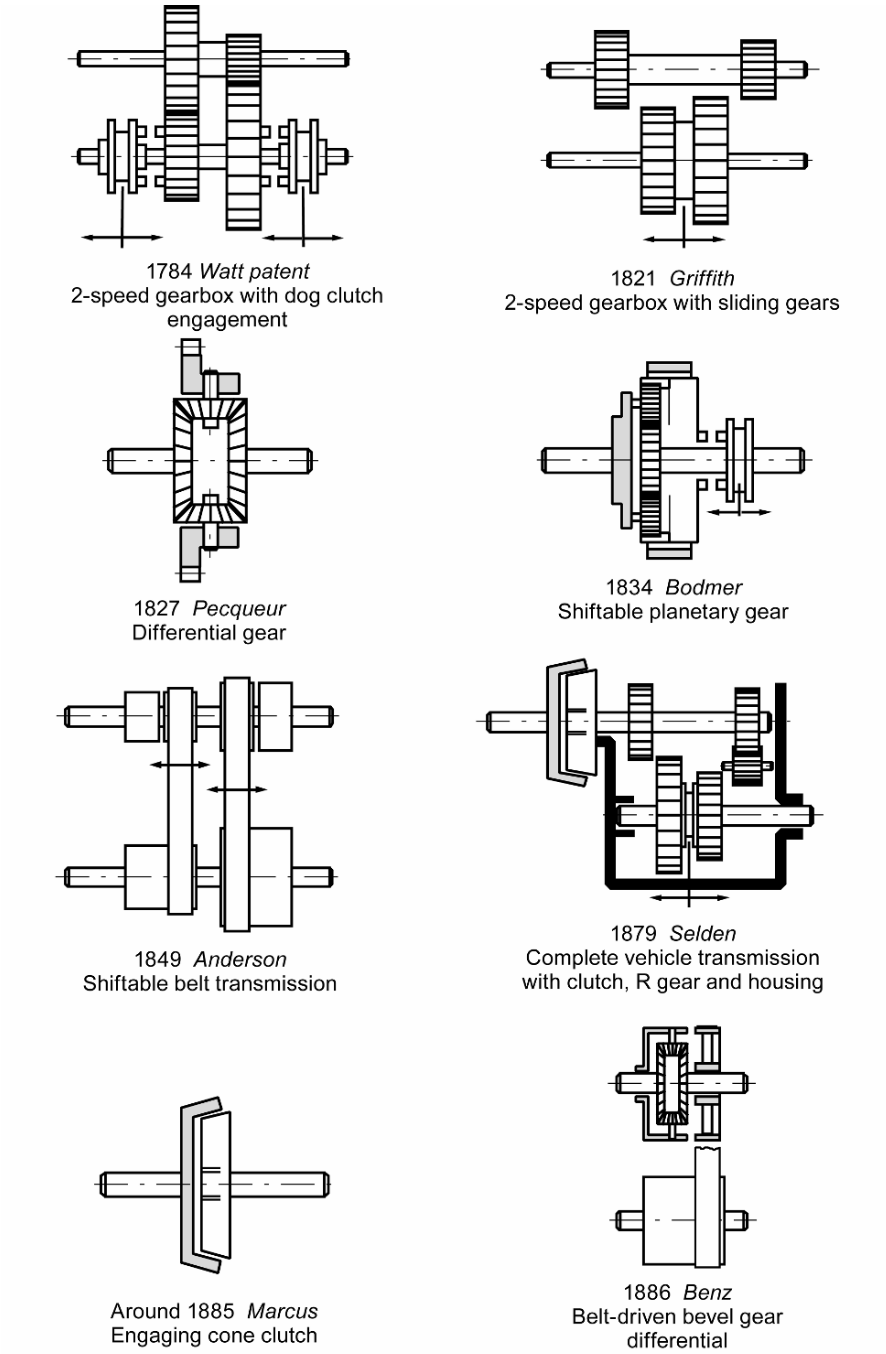


Fig. 1.12. Early vehicle components and gears

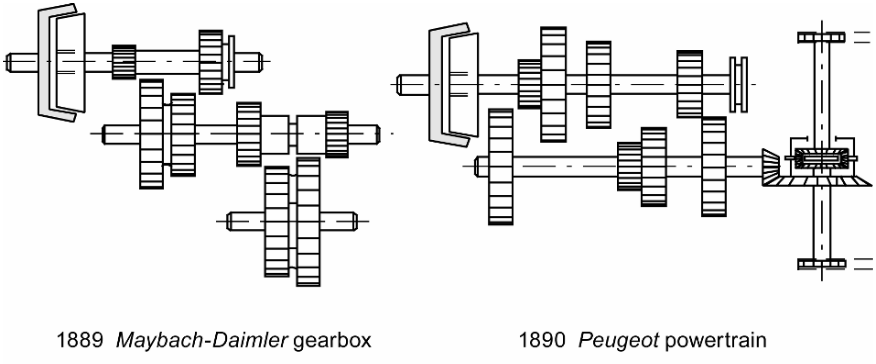


Fig. 1.13. Transmissions from the early days of the automobile

Actual production of road vehicles only began several decades later. In the year 1801, steam vehicle builders Evans and Trevithick solved the problem of torque adaptation, yet this still entailed interchanging a gear pair.

Already the beginning of the 19th century saw a series of important inventions (Figure 1.12). In 1821, Griffith revealed his sliding-gear transmission system, an inexpensive solution that was widely used well into the 20th century. Pecqueur managed in 1827 to equalize varying wheel speeds while cornering with the use of a differential.

In 1834, Bodmer designed a partially power-shiftable planetary gear. The change in gear ratio is achieved by disengaging the shifting dogs and tightening a brake band. As part of an overall patent for a vehicle with a piston engine, Selden patented a sliding-gear countershaft transmission with clutch and reverse gear in the year 1879.

It is remarkable how intensively research efforts already at the turn of the century were focused on the continuously variable transmission which is most ideally suited to internal combustion engines. Besides electrical and mechanical solutions, hydrostatic and even pneumatic ones were considered (Table 1.4). However, they did not gain acceptance, be it because of their insufficient power or mechanical complexity. The Föttinger torque converter (Table 1.6), invented in 1905 for ship propulsion systems, was first adapted to vehicle powertrains around 1925.

Direct drive was a crucial advancement. With it, Benz created the classic countershaft transmission with coaxial input and output still in use today. It was not yet included in Peugeot's exemplary powertrain from 1890 (Figure 1.13). The countershaft transmission design, with direct drive and four forward gears, proved a success. The basic problems of stepped gear change had been solved.

Around 1920, a further development phase began. Comfort had to be increased. The primary development goals were now making the gearshifting process easier and reducing noise by implementing ground and/or helical-cut spur gears or by reducing engine speed. Another important breakthrough was standard transmission, which was brought on the market for commercial vehicles in 1925. With it, gearboxes that were structurally identical or that varied only in their ratios and connec-

tions allowed for rational and inexpensive production. The gearbox has sliding gears.

The first facilitations in gearshifting date from the year 1915. The ZF Soden transmission included constant-mesh gearwheels, a preselector and synchronizing mechanisms. This transmission had preselection gearshifting: the driver sets a knob on the steering wheel to the desired gear and presses the pedal. The clutch is disengaged. As the shifting pedal is released, the preselected gear clicked automatically into place. The advantage of nearly effortless gearshifting could not compete with its disadvantages, such as the difficulty of adjusting the cable controls and the complex gearbox design.

In the case of a transmission from General Motors, the gearshifting process and subsequent power transmission was achieved by means of dogs with a cone synchronizer for speed synchronization between the shaft and the gearwheel. In 1928, Karl Maybach succeeded in improving vehicle running smoothness considerably by reducing gearing faults and engine speed with his auxiliary overdrive transmission and helical-ground gears. The quiet-running four-speed ZF Aphon gearbox originated at the same time. Its upper three speeds were synchronized with multiplates. In the ZF fully synchromesh gearbox for passenger cars (1934), all forward gears were already equipped with cone synchronizers.

The last conspicuous changes made to mechanical passenger car transmissions occurred after World War II, when more vehicles came out on the market, at first with rear-wheel drive, later with transverse engine and front-wheel drive – a development which has in the meantime spread to upper mid-size vehicles. For reasons of space, direct drive and coaxial design were abandoned and the engine, transmission and differential were combined into a single unit.

From about 1978, for fuel economy reasons, 5-speed transmissions with an increased overall gear ratio and finer ratio stepping gained increasing popularity for passenger cars. About ten years later, 6-speed manually shifted transmissions were also used in sports cars with longitudinal engines and rear-wheel drive. Especially in Europe, diesel engines in passenger vehicle gained in importance. Their image shifted from that of “Taxi-style” endurance machines to the active, high-torque engines. The transmission could compensate the lacking engine speed spread with more speeds. In 1999, VW began employing 6-speed manual transmissions for passenger cars with strong diesel engines mounted front-transverse. By 2005, six speeds were widely used among manually shifted vehicle transmissions.

Improvements in service reliefs all the way up to automatic gearshifting are a distinctly important line of development. From about 1956, Fichtel & Sachs furnished DKW (now Audi) with an electrically controlled, semi-automatic clutch, the *Saxomat*. This system consists of a centrifugal master clutch and a vacuum-operated gearshifting clutch. Upon contact with the gearshift lever, the gearshifting clutch is opened by a vacuum-controlled servo device. When the gearshift lever is released, air is slowly released to the servomechanism through a nozzle, thus engaging it. Pressing the accelerator pedal accelerates the air supply and thus the engaging motion. In comparison with a vehicle with a foot-activated clutch, driving comfort is significantly increased. In 1967, VW presented a semi-automated three-speed torque converter clutch transmission (TCCT) for passenger

vehicles. From about 1995, a first generation of automated manual transmissions was introduced for passenger cars and light commercial vehicles up to 3.5 t. They were based on the concept of "add-ons", i.e. the attachment onto existing mass-produced transmissions of automated actuators for clutch and gearshifting. Figure 1.11e illustrates such an "add-on" version as exemplified by the MT75 5-speed transmission installed at that time in the Ford Transit. The basic concept of "adding on" actuators was retained for the second generation of AMT as well. In the third generation, from about 2008, the peripheral parts were integrated.

Already in the year 1925, H. Rieseler designed an automatic transmission comprising a torque converter and rear-mounted planetary transmission. He thereby designed a transmission, the essential components of which – torque converter with planetary gear shifted by means of clutches and brakes – are now typical for all conventional automatic transmission systems. Rieseler had made an extraordinary contribution, the advantages of which were not yet recognized by subsequent design engineers. The latter consistently sought only to replace the mechanical clutches with a fluid clutch. The conventional automatic transmission, consisting of a torque converter (some with a hydrodynamic clutch), 3- or 4-stage planetary gear set and hydraulic control, began to become established as of 1939. The manufacturing technology required for this was developed in the USA.

The first mass-produced transmission of this kind was the General Motors *Hydramatic*. These transmissions spread rapidly in the USA after World War II, capturing market shares of around 85%. In Europe on the other hand, conventional automatic transmissions for passenger cars only reached a market share of around 13%. In 1953, Borgward developed the first automatic transmission designed in Germany. It had a powershift countershaft transmission with a front-mounted torque converter used only for starting. Daimler-Benz followed in 1961 and ZF in 1965 with their own designs. Daimler-Benz still had the old design reminiscent of the *Hydramatic* transmission, with planetary gear transmission and front-mounted fluid clutch. These automatic transmissions underwent constant development aimed at fuel conservation. The slip-controlled torque converter lock-up clutch as well as transmissions of up to 8 speeds for increasing the range and improved adaptation of ratios became standard.

Under competition by dual clutch transmissions, the field of conventional automatic transmissions has been focusing since around 2003 even more on spontaneity, dynamics and fuel consumption in order to open up further potential. The dual clutch transmissions going into production prior to 2010 predominately have torque ranges larger than 300 Nm and have wet-operating clutches. Dry dual clutches are presently being developed for transmissions below 300 Nm.

The continuously variable transmission reappeared fifty years after its first development. Van Doorne's *Variomatic* was developed in 1950, and in 1958 it became the first mass-produced continuously variable transmission. The power was transmitted by rubber V-belts and V-belt pulleys, the diameter of which could be varied by axial displacement. In the *Variomatic*, centrifugal weights and a membrane acted on by vacuum achieved this adjustment of the pulleys. On the output side, the pressure is produced by a spring. In such a design with two parallel mounted belts a differential is unnecessary. The difference in rotational speed is

compensated by belt slip. The rubber V-belts placed a limit on power. The permissible input torque was around 100 Nm. The transmission was therefore only suitable for small passenger cars.

Van Doorne then conceived the notion of the “steel V-belt”. The thrust link chain consists of a steel belt made up of thin belts, onto which the thrust links are pushed, connected to the V-belt pulleys. This transmission, developed around 1970, was ready for use around 1975 and went into production around 1987. The Audi *Multitronic* started production in 1999 as a continuously variable transmission with a tensional link chain and wet master clutch. This transmission serves mid-size vehicles of up to 350 Nm engine torque. While continuously variable passenger car transmissions can claim a considerable market share for small cars in Japan, they appear, especially in Europe, not to have lived up to prior expectations. In the case of small cars, especially weight and costs speak against the continuously variable transmission. It thus appears that automated manual gearboxes have become more competitive in the European small car market.

Until the World War II, commercial vehicle transmissions were distinguished from passenger vehicles essentially only in dimension. This then changed fundamentally. Payloads increased as new tyres could take on heavier loads; trucks began being used not only regionally but also for long-distance transport; the motorway network was expanded etc. – all this necessitated a larger range of ratios (i.e. a greater overall gear ratio) and thus more gears.

The initial development goals for mechanical transmissions for commercial vehicles were low weight (= larger payload), noise reduction and improved ease of use with the introduction of synchronizers. One important requirement was a long service life of up to 1 million km. Initially, five to six speeds were sufficient, although front-mounted splitter units already provided a finer stepping of the overall gear ratio. The 6-speed gearbox was expanded to 12 speeds. The increase in the specific power output (kW/t) of commercial vehicles then led to the need for an increased overall gear ratio. Transmissions with nine or more speeds were developed. For better fuel economy or, alternatively, better performance, transmissions with twelve to sixteen speeds became common for heavy trucks in the early 1970s. Such transmissions are designed as multi-range gearboxes (see Chapter 6).

Due to problems concerning service life and cost, synchronizers did not become as established in commercial vehicle gearboxes as in passenger cars. While passenger cars already had fully synchronized transmissions before World War II, the first fully synchronized commercial vehicle transmission did not come onto the market until 1957 with the ZF S 6-55. But especially in Europe, more and more commercial vehicle transmissions were equipped with synchromesh to ease the gearshifting process. Other approaches to improving ease of operation were also explored. The companies Faun and Siemens began developing the Symo gearshift mechanism in 1954. In this engine-based synchromesh, the electronically controlled gear is engaged at the exact moment when the element to be engaged is synchronized. The electronics also control acceleration/deceleration during shifting. In critical situations, such as steep downhill slopes or hills, it is possible that equalization of rotational speed by the engine may not alone be sufficient, or it may not be executable if the electronic system fails. Since this situation – danger-

ous for the driver, the vehicle and the load – could never be completely excluded, the system never went into mass production. Around 1970, an attempt was made to make commercial vehicle transmissions semi-automatic by developing torque converter clutch transmissions (Figure 1.11d). The combination of a torque converter with a conventional separating clutch and a 6 to 16 speed transmission made moving-off with heavy tractor-trailer units easier. The torque converter increased the overall gear ratio. Transmissions of this sort are indeed in use, but have not become popular, claiming a mere 1 to 2% of the market share. The reasons for this are mostly to be sought in their high price (due to their complexity) as well as in increased fuel consumption.

Semi-automated commercial vehicle transmission designs have been coming onto the market since about 1985. Representative examples of such systems are the AVS system (automatic preselection shifting) by ZF or Mercedes-Benz's EPS system (electronic pneumatic shift). Fully automatic transmissions have become pervasive among heavy-duty commercial vehicles since about 2000. In such systems, both the moving-off and gear-changing processes are completely automated. As is the case for automated transmissions for passenger cars, commercial vehicle transmission designs have also taken the "add-on" route towards integrating peripheral parts into the transmission.

Automatic transmissions have not yet become common in trucks. This has to do with questions of economy and reliability. When commercial vehicles are exported to developing countries, the main concern is that they be easy and reliable to maintain. However, automatic transmissions are standard for city buses (Figure 1.11g). 1971 saw the first production version of a continuously variable hydrostatic power-split transmission (via a planetary gear set) for city delivery vehicles, the Sundstrand *Responder*. It proved unsuccessful however, and production was discontinued. Later attempts to utilize hydrostatic units with mechanical power-splits via planetary gears in city buses were also unsuccessful. Instead, power-split hydrostatic continuously variable transmissions have been widely used in the production of tractors of various manufacturers since about 1996.

Presently, fuel cell related research is focusing intensively on the development of electrical drives, particularly for city buses.

1.2.4 Development of Gear-Tooth Systems and other Transmission Components

The components of automotive transmissions are themselves in a state of evolution. We will now examine the development of components such as gearwheels, shafts, bearings, synchronizers and clutches as well as electronic controls (Table 1.5).

The most important component is the gearwheel. It would be impossible to provide historical evidence of the first gearwheels. But gear drives were used early on both for increasing human or animal power and for exploiting wind and water power. We can assume that the use of wooden gearwheels with crossed axes – similar to the bullock gear systems still in use for irrigation in Egypt today – is one

of the earliest examples of the use of the gearwheel (Figure 1.10). Derived from these primeval gearwheels are mill drives and series-connected geared drives used to realize greater transmission ratios. Designs of such systems are recorded in great diversity in contemporary drawings. The use of gearwheels for the transmission of power has proven particularly fruitful in mining and mill construction. The great artist and inventor Leonardo da Vinci provided the foundations for our present-day machine component already back in the 15th century.

The scientific study of gears began at the end of the 17th century with de la Hire. Euler, Willis and Reuleaux continued this work. The law of gears as it was finally formulated by Saalschütz in 1870 states:

> *There will be uniformity of transmission of motion between two meshing gearwheels where the common normal of both tooth curves passes through the pitch point C at any contact point of the flanks.*

The creation of theoretically correct flank profiles on a mathematical and graphical basis was the prerequisite of mechanical gear technology. The development of the rolling process was groundbreaking for industrial gearwheel production (Table 1.5).

While lantern and cycloid gears had previously been the most important types of gear, today it is the involute. Because of its straight-flanked tool, which meshes on the base circle, it can be manufactured and measured precisely. Moreover, it has the characteristic of being insensitive to changes in gear centre distance.

Developments since 1980 have opened up new possibilities in gearwheel manufacturing. With numerically controlled tooth-hobbing machines, the rotary and longitudinal movements required to produce the tooth profile are controlled and synchronized electronically. In this way, arbitrary tooth profiles can be produced for special purposes, e.g. for low-noise gear pumps, which however still satisfy the requirements of the gear law.

Table 1.5. Chronological development of gear tooth systems and other transmission components

2000–1000 BC	Spur gears with lantern gear, worm gears. Transport of heavy loads on rollers
230 BC	*Philon v. Alexandria* Multi-lever wheel with gear rack
100 BC	Sun wheels and planetary gears in the astrolabe of Anticythera
1300	*Giovanni da Dondi* Astronomic clock with internal gearing and elliptical gearwheels
15th C.	Idea of helical gears Sprocket wheels for link chains
15th C.	*Leonardo da Vinci* “Book of movement”, “Book of gravity”, “Book of moment of force”, principle of virtual speeds, principle of independent super–position of movements, principle of the potential lever
15th C.	Gearwheels for transmitting movement in windmills
1639	*Désargues* Cycloid profiled gearwheels
1694	*De La Hire* Founder of gearing science, point gearing: teeth paired with points or journals, pitch circles

Table 1.5. *(continued)*

1733	*Camus* Pair gearing, teeth paired with teeth, cycloid toothing	**1902**	*Stribeck* Work on the chief characteristics of plain bearings and roller bearings
1754	*Euler* Involute toothing	**1903**	First deep groove ball bearing
1765	*Euler* Curvature centre-points	**1907**	*SKF* Self-aligning ball bearing
1780	*Wasborough/Pickard* Thrust crank transmission	**1908**	*Norma* First useable cylindrical roller bearing
1820	Axial ball bearing with cage as bearing for castors	**1912**	*Humphrie* Synchromesh to make changing gear easier
1820	*Tredgold* Beginning of gear-wheel strength calculation	**1915**	*Maag* Gear grinder
1850	*Willis* Systematic classification of gears: Modules: possibility of combining any gearwheels from the same module	**1916**	*v. Soden* Patent application for synchromesh
		1925	*Gleason* Hypoid gear
		1927	*ZF* Bevel grinding
1856	*Schiele* Hobbing process useable with insertion of index gears	**1930**	*Palmgren* Method for calculating rolling bearings based on the concept of service life
1857	Application and spread of rolling bearings in bicycles, first patented cup-and-cone bearing	**1934**	Determination of module series
		1938	*ZF* Introduction of lock synchronizer
1865	*Reuleaux* Description of “general gear hobbing”	**1938**	*Simmer* Patent for rotary shaft seal
1869	*Surirey* Ball bearing		
1872	*Wagen-Thorn* Gear shaping method	**1956**	*Fichtel & Sachs* *Saxomat* Electrically controlled semi-automatic clutch comprising centrifugal master clutch and vacuum-activated gearshifting clutch
1876	*Reuleaux* Line of action		
1881	*Hertz* Theory of contact and pressure of solid elastic bodies; Hertzian stress		
1882	*Bilgram* Invention of bevel gear production	**1955**	*Novikov* Round-flank toothing for unhardened spur gears
1883	*Petroff/Tower/Reynolds* Hydrodynamic lubricant film theory in plain bearings	**1982**	Transmission control of automatic transmissions with microprocessors
1885	*Marcus* Cone clutch for automobiles (Figure 1.12)	**1983**	Free tooth formation according to the law of gears using numerically controlled gear hobbing machines
1887	*Grant* Gear shaping method for helical gears		
1890	*Sachs* Patent on precision bicycle wheel hub	**1997**	*Mercedes-Benz* & *Siemens* combine in the automatic transmission W5A 180 electronic transmission control, actuating elements, sensors and hydraulics to one mechatronic system and place it inside the transmission
1895	*Maybach* Gate shift for automotive transmissions, grouping gears in “gates”		
1897	*Pfauter* Universal gearwheel milling machine for spur gears, worm gears and helical gears	**>2000**	System and information networking of vehicle components

Initially, heat-treated steels were used to make gearwheels. Case-hardened steels soon became necessary in order to improve performance while simultaneously reducing weight. To reach the level of quality necessary for noise reduction, gear-

wheels have to be shaved after hobbing or ground after hardening. Current methods of machining after heat treatment are described in Chapter 16.

Other important transmission components such as rolling bearings, clutches and synchronizers were then developed in the second half of the 19th century and the beginning of the 20th. Since about 1995, there have been essential innovations in automotive transmissions in the highly dynamic fields of electronics, software, function development as well as system and information networking.

Finally, it should be mentioned that toothed gearing, as a means of converting torque and rotational speed, has a better power/weight ratio than other converters such as belt or chain drive, hydrodynamic or hydrostatic transmission or the electric motor.

1.2.5 Development of Torque Converters and Clutches

Initially, the individual components of automatic transmissions developed slowly, but this development has accelerated markedly, especially considering the complexity of such systems.

The foundation was laid by H. Föttinger in 1905, when he had a torque converter patented and a hydrodynamic clutch shortly thereafter. Föttinger constructed this torque converter for use in ships and never considered installing one in an automobile. The development of the torque converter is a good example of the systematic development of a transmission component (see Table 1.6 and Chapter 10). As an electrical engineer, Föttinger recognized the potential of combining a hydrodynamic prime mover (pump) with a machine (turbine) and first developed the idea theoretically.

It lasted almost two decades until attempts were made to apply Föttinger's torque converter and clutch to an automotive transmission. The Trilok converter devised by Spannhake, Kluge and van Santen combined the less efficient torque converter with the more efficient clutch. By mounting the reactor in the housing by means of a freewheel unit, the reactor runs freely when the reaction torque is discontinued, that is, exactly at the moment that the output torque falls below the input torque. The torque converter becomes a clutch and can thereby make use of the high level of efficiency of the fluid clutch in the high speed range. This combination has long been prevalent in automatic transmissions worldwide. In 1925, Rieseler recognized the potential inherent in the torque converter as both a moving-off and limited torque conversion mechanism for automatic vehicle transmissions. In the USA, the technology for mass production of hydrodynamic clutches and torque converters was developed shortly before World War II.

In order to bypass the slip necessary for power transmission in the Trilok converter, the pump and the turbine have been fitted with a lock-up clutch in the main driving ranges. This lock-up clutch has been slip-controlled since about 1994, thus making it possible to lock the converter even in lower gears and at low engine speeds. Developments such as the turbine torsional vibration damper or the two-damper converter have further improved the filtering of engine excitation.

Table 1.6. Chronology of the development of torque converters, clutches and their use in conventional automatic transmissions

1900	Steam turbines start to replace steam engines. Ship propulsion systems require a reversible reduction gearbox approx. 1:4 for several 1000 hp between the turbine and the propeller
1902	*Föttinger* is commissioned by the “VULCAN” shipyard where he works to study this problem; the largest gearwheel transmissions deliver only 400 hp
1905	*Föttinger's* patent specification on 24 June, with the basic idea of hydrodynamic power transmission. Integration of pump and turbine to reduce losses, German Patent No. 221422
1910	German Patent No. 238804 for hydrodynamic clutch = converter without reactor
1917	Gearwheel transmissions catch up with and displace torque converters in marine engineering. But the significance of the hydrodynamic clutch continues to increase
1925	*Rieseler*, a colleague of Föttinger, builds and tests an automatic vehicle transmission with torque converter and planetary gear unit
1928	The *TRILOK* consortium in Karlsruhe (Spannhake, previously a colleague of Föttinger, Kluge and van Sanden) develop the Trilok converter. Both phases run in a single fluid circuit, first the torque phase (η_{max} = 0.8–0.9) and then the clutch phase (η_{max} = 0.98)
1939	*General Motors* develops the first mass-produced (10 million) fully automatic vehicle transmission, the Hydramatic, with hydrodynamic clutch
1948	*Dynaflow* transmission by GMC with 4-phase torque converter
1955	*Borgward* Borgward builds the first automatic mass-produced transmission in Germany, with hydrodynamic converter and rear-mounted 2-speed transmission
1961	The first in-house development by *Daimler-Benz*. Hydrodynamic clutch with rear-mounted 4-speed 2-range planetary transmission
1965	3 HP 12 from the gear manufacturer *Zahnradfabrik Friedrichshafen AG*: Trilok sheet metal converter with rear-mounted 3-speed Ravigneaux planetary gear set
1965	Trilok converter with lock-up clutch for commercial vehicle torque converter clutch transmission. Cast pump, sheet metal turbine
1980	Trilok converter with lock-up clutch for automatic passenger car transmission
1994	*ZF* Slip-controlled lock-up clutch in passenger car transmission 5 HP 30, lock-up also in lower gears
1996	*LuK* Turbine torsional vibration damper, closing of the lock-up clutch at low engine speeds
2006	*ZF-Sachs* Two-damper torque converter for broadband filtering of engine excitation

1.2.6 Investigation of Phenomena: Transmission Losses and Efficiency

For the successful and reliable utilization of automotive transmissions, a great variety of phenomena need to be researched. Hertzian stress, tooth root strength,

elasto-hydrodynamic lubrication and operational fatigue strength are just a few examples.

One representative example of historic development is the phenomenon of friction. Heat is generated in transmissions by friction. Friction occurs when tooth flanks and bearing parts make rolling or sliding contact from shifting and from circulating, flowing oil.

Heat generation in transmissions was soon a matter of great interest. Determining transmissions losses, i.e. toothing, bearing and churning losses, became increasingly important. Inquiry into the friction coefficient along the contact path became topical. An understanding of the transmission's efficiency and how this is related to design, load and speed is essential for any energy-saving measures. Table 1.7 provides an overview of research into these phenomena.

Table 1.7. Chronology of the development of research into transmission loss phenomena

1869	*Reuleaux* First formulations to determine frictional work losses
1883	*Ernst* Losses in spur gears and perpetual screws
1886	*Lewis* Measurement of efficiency of worm gears
1911	*Rickli/Grob* Measuring loss in transmissions with a torque test bench. The reading is the actual loss, and no longer the input and output power
1946	*Hofer* Approximation formula supported by measurements for calculating the efficiency of a gear stage
1954	*Niemann* develops a formula for calculating efficency $\eta = 1 - \frac{P_V}{P_1}$ $\eta = 1 - \frac{i \pm 1}{7\, i\, z_1}$
1960	*Niemann, Ohlendorf* Systematic experiments and calculations to determine transmission losses. Gear losses in the mixed friction area (power loss through dry friction), information on churning losses and bearing losses
1965	*Hill* investigates the connection between gearing geometry and efficiency; he calculates the transmission efficiency at a constant average coefficient of friction
1967	*Lechner* Scuffing resistance with spur gears made of steel. Heat generation in gearwheels. Investigation of the phenomenon of gear scuffing as a function of gearing geometry and operating conditions
1971	*Duda* Detailed analysis of the influences of tooth geometry on efficiency
1972	*Schouten* Rolling, sliding action as elasto-hydrodynamic problem
1975	*Rodermund* Elasto-hydrodynamic lubrication with involute gearwheels. Losses with variable coefficient of friction along the contact path
1980	*Lauster* Investigation and calculation of the thermal economy of mechanical transmissions
1982	*Walter* Investigation of splash lubrication of spur wheels at circumferential speeds of up to 60 m/s
1985	*Funk* Heat dissipation in transmissions under quasi-static operating conditions
1988	*Mauz* Hydraulic losses of spur gear systems at circumferential speeds of up to 60 m/s
1990	*Greiner* Investigation of lubrication and cooling of injection-lubricated spur gear systems

1.2.7 Historical Overview

The development of automotive transmissions can, historically speaking, be split into four stages:

Ca. 1784 to 1884 Recognition of the fact that the torque/speed characteristics of steam engines and internal combustion engines must be adapted to the load by means of a transmission in order to obtain the maximum power. The first solutions were variable-speed transmissions with sliding or constant-mesh gears.

Ca. 1884 to 1914 Hunt for the correct principle for torque/speed conversion. Besides toothed gearings, a great diversity of transmission designs was attempted: chain, belt and friction gears, electric, hydraulic and even pneumatic transmissions, geared transmissions and especially continuously variable transmissions were tested. All the while, every transmission design was specially tailored for a particular vehicle.

Ca. 1914 to 1980 Geared transmissions became more accepted because of their high power/weight ratio. The notion of standardized gearboxes that could easily be modified for use in different vehicles became established. Their development has continued through the subsequent decades up to the present time in terms of service life, reliability, noise level and ease of operation (synchromesh, conventional automatic transmission, shifting with uninterrupted traction, semi-automated transmission with electronically controlled shift aid). The number of speeds and the overall gear ratio constantly increased. Mass increases in motorization have been a crucial impetus behind the development of service reliefs for passenger cars.

Ca. 1980 to date The main focus of further research has been “individual” solutions tailored to particular uses (see also Chapter 2.5 “Trends in Transmission Design”). The palette of transmission designs has gotten much larger. Alternative transmission designs for passenger cars are competing with each other: manual transmissions, automated manual transmissions, dual clutch transmissions, conventional automatic transmissions, continuously variable transmissions and hybrid drives. Geared transmissions have 5–8 speeds. All-wheel technology has gained in importance. In the case of commercial vehicles, geared transmissions have 6–16 speeds and the greatest possible overall gear ratios. In the European heavy-duty commercial vehicle sector, automated manual gearboxes have become widespread. Now even commercial vehicles have attained a high level of operational comfort and can be driven

by practically anyone. There are also important developments in both passenger and commercial transmission technology in the fields of electronics, software, function development as well as in system and information networking.